

Advanced System-level Model Reduction Method for Multi-converter DC Power Systems

Lin Zhu, Xueshen Zhao, Xialin Li, Li Guo, Bo Zhao, Zhanfeng Deng, Hao Lu,
and Chengshan Wang, *Senior Member, IEEE, Fellow, CSEE*

Abstract—For dynamic stability analysis and instability mechanism understanding of multi-converter medium voltage DC power systems with droop-based double-loop control, an advanced system-level model reduction method is proposed. With this method, mathematical relationships of control parameters (e.g., current and voltage control parameters) between the system and its equivalent reduced-order model are established. First, open-loop and closed-loop equivalent reduced-order models of current control loop considering dynamic interaction among converters are established. An instability mechanism (e.g., unreasonable current control parameters) of the system can be revealed intuitively. Theoretical guidance for adjustment of current control parameters can also be given. Then, considering dynamic interaction of current control among converters, open-loop and closed-loop equivalent reduced-order models of voltage control loop are established. Oscillation frequency and damping factor of DC bus voltage in a wide oscillation frequency range (e.g., 10–50 Hz) can be evaluated accurately. More importantly, accuracy of advanced system-level model reduction method is not compromised, even for MVDC power systems with inconsistent control parameters and different number of converters. Finally, experiments in RT-BOX hardware-in-the-loop experimental platform are conducted to validate the advanced system-level model reduction method.

Index Terms—Closed-loop reduced-order model, instability mechanism, open-loop reduced-order model, stability analysis, system-level model reduction method.

I. INTRODUCTION

IN a multi-converter medium-voltage DC (MVDC) power system, stability analysis is the most significant research issue due to negative incremental resistance characteristics of constant power loads (CPLs) [1]–[3]. Theoretically, dynamic stability analysis can be carried out by constructing a system-level full-order model, which includes all complicated dynamic performances. However, this model is not widely

accepted so far, primarily due to its enormous complexity [4], [5]. Therefore, a model order reduction method is extremely essential to reduce complexity of MVDC power system dynamic stability analysis [6], [7].

To date, the majority of reduced-order models (ROMs) can be obtained through the individual model reduction method (IMRM), which is divided into two steps, as shown in Fig. 1. First, by ignoring some control parameters, converter-level ROM is obtained separately without system interconnection. Furthermore, system-level ROM (SLROM) is established by connecting converter-level ROMs following network topology. Literature [4] proposes a linearized IMRM, which can be used to obtain sufficiency conditions for stable operation of a droop-controlled DC microgrid. However, only system oscillation dynamics around 25 Hz can be evaluated, mainly because of the neglected voltage control parameters. In literature [5], a simplified equivalent model of a DC microgrid is presented, which is able to analyze dynamic stability around 33 Hz [8]. But this microgrid is based on voltage single-loop control rather than the most commonly used voltage current double-loop control [9]. An equivalent RLC circuit for a converter can be built by [10], as long as its current control is ten times faster than its voltage control. Further, an equivalent second-order model considering multiple RLC parallel circuits in a DC system is established. However, DC voltage dynamics can be estimated only in a narrow oscillation frequency range (around 10 Hz), which is attributed to the fact that current control parameters are not considered by the second-order model. In summary, the above SLROMs can effectively evaluate system dynamics around a certain oscillation frequency, but their accuracy over a wideband oscillation frequency range (e.g., 10–50 Hz) needs further verification [11]. There is no doubt the applicability of the model will be limited when its order is reduced by ignoring some control parameters in a DC system. So, for a multi-converter MVDC power system with droop-based double-loop control, how to build its SLROM without neglecting any control parameters is still an unsolved problem.

It is well known when an unstable oscillation occurs in a DC system, there is an urgent need to investigate its instability mechanism [12]. The SLROMs developed by [8]–[10] are all closed-loop models, which are able to evaluate the system stability without revealing the instability mechanism [13]. Instability mechanism of multiterminal DC (MTDC)/AC power system is revealed by [14], [15] from an open-loop modal coupling perspective, which is interaction of converter control dynamics with passive components of the system. However,

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L. Zhu, X. S. Zhao, X. L. Li (corresponding author, email: xialinlee@tju.edu.cn), L. Guo, H. Lu and C. S. Wang are with the Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China.

B. Zhao is with the Research Institute of State Grid Zhejiang Electric Power Co., Ltd., Hangzhou 310014, China.

Z. F. Deng is with the State Grid Global Energy Interconnection Research Institute, Beijing 102209, China.

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open-loop modal coupling of [14], [15] studies only a single converter rather than the whole system. As the instability mechanism is revealed, the corresponding stabilization method should be presented, subsequently [16]. A simplified circuit model of the DC system is obtained in [17], which reveals the unstable oscillation mechanism caused by equivalent LC filter and CPL intuitively. Moreover, this unstable oscillation can be damped by a state-feedback control method presented in [17], but effectiveness of this method depends on real-time input current data of all CPLs. Compared to [17], a frequency-dependent virtual impedance method consisting of a parallel RL branch is presented by [18], and reliability of this method relies only on local voltage and current signals of each LRC. Compared to stabilization control methods proposed in [17], [18], required damping of the system can also be provided by current control loop [19], [20]. However, undesired dynamic interaction between multiple converters in a DC system makes control parameter adjustment not as simple as in single converter situation [21], [22]. Therefore, for a multi-converter MVDC power system with droop-based double-loop control, how to provide theoretical guidance on adjustment of its control parameters remains an unsolved problem.

With the above unresolved issues, the main contributions can be drawn as:

1) An advanced system-level model reduction method (SLMRM) is proposed, which is divided into four steps to establish a system-level equivalent reduced-order model (SLROM) of a multi-converter medium-voltage DC (MVDC) power system, as shown in Fig. 2. Moreover, analytical equations for all parameters (e.g., filter parameters, current control,

voltage control and droop control parameters) between system and its SLROM are established. Since no control parameters are neglected, dynamic stability of the system can be accurately evaluated by its SLROM. In addition, effectiveness of the SLMRM is not affected even for MVDC power systems with inconsistent control parameters and different number of converters.

2) With cancellation between some zero-poles, the SLROM (fourth-order model) can be further reduced to a typical second-order model. Moreover, oscillation frequency and damping factor of DC bus voltage in a wide oscillation frequency range (such as 10–50 Hz) can be evaluated accurately.

3) With the frequency-response curves of the transfer functions (including current control and voltage control loops, etc.) of the SLROM, instability mechanisms (e.g., unreasonable current control parameters) of the multi-converter MVDC power system can be revealed intuitively. In addition, theoretical guidelines for adjustment of control parameters can be obtained in order to damp unstable oscillations.

The rest of this paper is organized as follows: Section II describes a typical multi-converter MVDC power system and its open-loop reduced-order model (OLROM). In Section III, closed-loop reduced-order models (CLROMs) considering droop-based double loop control are built step-by-step. Then detailed dynamic stability analysis and experimental verification are provided in Section IV. Section V concludes.

II. OPEN-LOOP REDUCED-ORDER MODEL

In this section, the first step of the SLMRM is introduced in detail. An OLROM of a typical multi-converter MVDC power system is established.

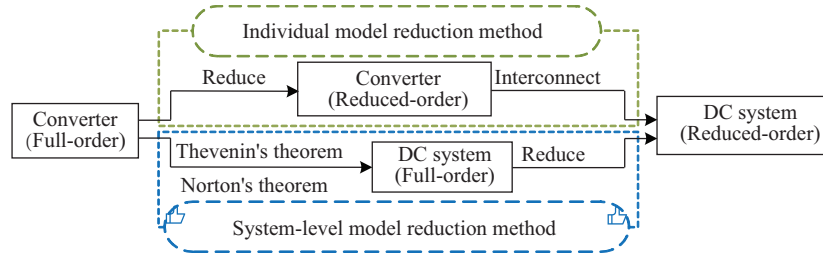


Fig. 1. System-level and individual model reduction method.

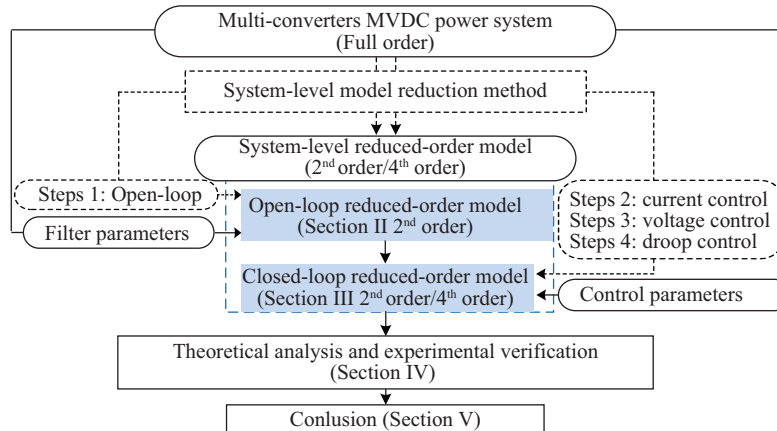


Fig. 2. System-level model reduction method for multi-converter MVDC power system.

A. Topology and Equivalent Circuit Model of multi-converter MVDC Power System

A multi-converter MVDC power system with n LRCs and m CPLs is depicted in Fig. 3(a).

After equivalent transformation of relevant power devices, an equivalent circuit model of the system is obtained, as shown in Fig. 3(b) [19]. Where, V_{sx} and D_x are the source voltage and duty factor of x^{th} LRC respectively ($x = 1, 2, \dots, n$), L_{fx} and C_{fx} are equivalent output filter parameters of x^{th} LRC, I_x is inductor current of x^{th} LRC, V_{Lh} and I_{Lh} are voltage and current of h^{th} CPL respectively, C_{Lfh} is input filter capacitor of h^{th} CPL ($h = 1, 2, \dots, m$), I_{ch} is cable current, R_{ch} and L_{ch} are cable resistors and inductors, respectively. The distributed capacitor and resistor of the cable are small, so their influence is ignored.

Figure 3(b) can represent the equivalent circuit model by $n + 2m + 1$ nonlinear differential equations, when V , I_x , I_{ch} , and V_{Lh} are selected as state variables [19].

B. Open-loop Reduced-order Model Considering Dynamic Interaction among Converters

According to Norton's theorem, multiple parallel CPLs in Fig. 3(b) can be simplified as the circuit in Fig. 4(a). This simplified circuit model can be represented by $n + 3$ nonlinear differential equations, when V , I_x , I_c , and V_L are selected as state variables. Based on Thevenin's theorem, OLRM shown in Fig. 4(b) can be obtained from Fig. 4(a). Its order can be reduced to 4 by choosing V , I (or $\frac{dV}{dt}$), I_c , and V_L as state variables [19]. With linearization, a small signal model is built and the general expression of control-to-output transfer function $G_{vdx_cable}(s)$ for x^{th} LRC can be written as (1). $G_{vdx_cable}(s)$ is not only relevant to filter parameters of x^{th} LRC but also relevant to other LRCs. L_{eq} and C_{eq} are equivalent filter parameters, ω_0 , ω_{cz} , and ω_{cp} are corresponding natural oscillation frequency, ζ_0 , ζ_{cz} , and ζ_{cp} are corresponding damping factor.

$$G_{vdx_cable}(s) = \frac{\left(\frac{V_{sx}}{C_{eq}L_{fx}}\right)(s^2 + 2\zeta_{cz}\omega_{cz}s + \omega_{cz}^2)}{(s^2 + 2\zeta_{op}\omega_{op}s + \omega_0^2)(s^2 + 2\zeta_{cp}\omega_{cp}s + \omega_{cp}^2)} \quad (1)$$

$$\begin{cases} R_{eq} = \frac{V_L^2}{P_{eq}} \\ \frac{1}{L_{eq}} = \sum_{x=1}^n \frac{1}{L_{fx}} \\ C_{eq} = \sum_{x=1}^n C_{fx} + \sum_{h=1}^m C_{Lfh} \end{cases} \quad (2)$$

$$\begin{cases} \omega_{op} = \frac{1}{\sqrt{C_{eq}L_{eq} + L_{ceq}C_{Lfeq}}} \\ \omega_{cz} = \sqrt{\frac{1}{L_{ceq}C_{Lfeq}}} \\ \omega_{cp} = \sqrt{\frac{1}{L_{eq}C_{feq}} + \frac{1}{L_{ceq}C_{Lfeq}} + \frac{1}{L_{ceq}C_{feq}}} \end{cases} \quad (3)$$

As shown in Fig. 5, ω_{cz} is always bigger than ω_{op} and smaller than ω_{cp} . If ω_{cz} is ten times greater than ω_{op} , poles related to ω_{op} are dominant poles of the system, OLRM can be reduced to 2nd order. Even if the condition cannot be met, 2nd order CLROM can also be achieved by appropriate control bandwidth settlement, verified in Section IV-B in detail. Because ω_{cz} is only determined by cable parameters

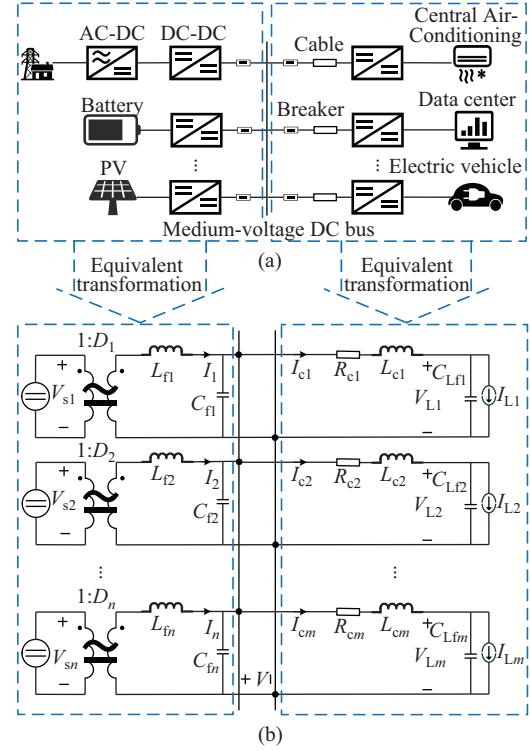


Fig. 3. Equivalent transformation. (a) Topology of a typical multi-converter MVDC power system. (b) Equivalent circuit model.

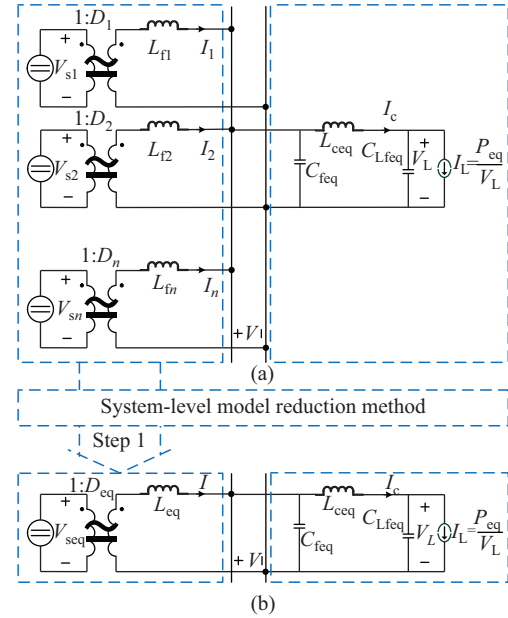


Fig. 4. Circuit model. (a) Simplified multi-converter model. (b) Equivalent single-converter model.

L_{ceq} and C_{Lfeq} , without influence of the output filter of LRCs, it will not be affected by control parameters [23]. On the contrary, ω_{op} can be significantly changed (from ω_{op} to ω_{os}) by control parameters of LRCs. When ω_{cz} is ten times greater than ω_{os} , CLROM is reduced to 2nd order successfully. In summary, to ensure cable parametric oscillation never plays a leading role (ω_{op} or $\omega_{os} \leq 10 \times \omega_{cz} \leq 10 \times \omega_{cp}$), OLRM can be reduced to 2nd order, and cable parameter L_{ceq} can be

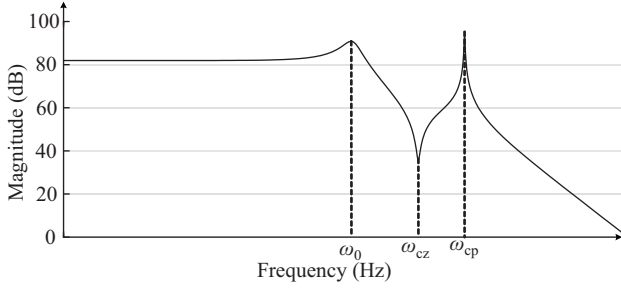


Fig. 5. Magnitude bode plot for transfer function $G_{vdx_cable}(s)$.

ignored. Control-to-output transfer function $G_{vdx}(s)$ of x^{th} LRC can be written as (4), as well as equivalent $G_{vdeq}(s)$ can be depicted as (5) [23].

$$G_{vdx}(s) = \left(\frac{V_{sx}}{C_{eq}L_{fx}} \right) \frac{1}{s^2 + 2\zeta_0\omega_0s + \omega_0^2} \quad (4)$$

$$G_{vdeq}(s) = \left(\frac{V_{seq}}{C_{eq}L_{eq}} \right) \frac{1}{s^2 + 2\zeta_0\omega_0s + \omega_0^2} \quad (5)$$

$$\begin{cases} \zeta_0 = -\frac{1}{2R_{eq}} \sqrt{\frac{L_{eq}}{C_{eq}}} \\ \omega_0 = \frac{1}{\sqrt{C_{eq}L_{eq}}} \end{cases} \quad (6)$$

III. CLOSED-LOOP REDUCED-ORDER MODEL

Based on step 1 OLROM, each step CLROMs considering dynamic interaction among converters are established from step 2 to step 4, as shown in Fig. 6.

A. Step 2: System-level Reduced-order Modeling Considering Dynamic Interaction of Current Control among Converters

It is assumed the ratio between current control parameters of each converter is the same as the ratio between their filter parameters. Substitute (4) to (7), control-to-inductor current transfer function $G_{idk}(s)$ of x^{th} LRC can be written as:

$$G_{idk}(s) = g_k G_{vdk}(s) G_{iv}(s) \quad (7)$$

where g_x is load sharing coefficient ($\sum g_x = 1$) of x^{th} LRC, $G_{iv}(s)$ is equivalent admittance, and $G_{iv}(s) = C_{eq}s - 1/R_{eq}$. In Fig. 6(a), $G_{icx}(s)$ is current controller of x^{th} LRC, and loop gain $T_{iix}(s)$ of current control of x^{th} LRC can be derived as $T_{iix}(s) = G_{idk}(s) \times G_{icx}(s)$. Then, current closed-loop transfer function $G_{iik}(s)$ of x^{th} LRC can be written as (8). It considers not only current control parameters of x^{th} LRC but also other LRCs.

$$G_{iix}(s) = \frac{g_x G_{vdx}(s) G_{icx}(s) G_{iv}(s)}{1 + \sum_{y=1}^n \{g_y G_{vdy}(s) G_{icy}(s) G_{iv}(s)\}} \quad (8)$$

Due to existence of $\sum I_x = I_{eq}$, system level transfer function $G_{iisys}(s)$ is obtained by dynamic coupling and interconnection $G_{iix}(s)$ to each other, as shown in Appendix (A-1). Expression of $G_{iisys}(s)$ (multi-converter condition) is consistent with equivalent current closed-loop transfer function $G_{iieq}(s)$ of the SLROM (equivalent single-converter situation).

As shown in Fig. 6(b), control-to-inductor current transfer function $G_{ideq}(s)$ of the SLROM can be written as:

$$G_{ideq}(s) = G_{vdeq}(s) G_{iv}(s) \quad (9)$$

As $G_{iceq}(s)$ is current controller of SLROM, and loop gain $T_{iieq}(s)$ can be derived as $T_{iieq}(s) = G_{ideq}(s) \times G_{iceq}(s)$. Then, current closed-loop transfer function $G_{iieq}(s)$ can be written as Appendix (A-2). Proportional and integral gains of current controller $G_{iceq}(s)$ are k_{pieq} and k_{iieq} , respectively.

As (A-2) is equivalent to (A-1), the following mathematical equations can be obtained.

$$\begin{cases} k_{pieq} = L_{eq} \sum_{x=1}^n \frac{g_x k_{pix}}{L_{fx}} \\ k_{iieq} = L_{eq} \sum_{x=1}^n \frac{g_x k_{iix}}{L_{fx}} \end{cases} \quad (10)$$

As expected, k_{pieq} is a function of k_{pix} , g_x , and L_{fx} , while k_{iieq} is a function of k_{iix} , g_x , and L_{fx} . With (10), mathematical relationships of current control parameters between multi-converter and equivalent single-converter systems are established.

Based on comparative analysis of the bode graph of $T_{iix}(s)$ and $T_{iieq}(s)$ (or $G_{iix}(s)$ and $G_{iieq}(s)$), the instability mechanism (unreasonable current control parameters) can be revealed intuitively. Moreover, theoretical guidance for adjustment of control parameters can also be given.

B. Step 3: System-level Reduced-order Modeling Considering Dynamic Interaction of Voltage Control among Converters

Ratio between voltage control parameters of each converter is assumed to be the same as the ratio between their rated output powers. Substitute (8) to (11), voltage open-loop transfer function $G_{ivdx}(s)$ of x^{th} LRC can be written as:

$$G_{ivdx}(s) = \frac{G_{iix}(s)}{g_x G_{iv}(s)} \quad (11)$$

As shown in Fig. 6(a), $G_{vcx}(s)$ is voltage controller of x^{th} LRC, and loop gain $T_{vivx}(s)$ of voltage control of x^{th} LRC can be derived as $T_{vivx}(s) = G_{ivdx}(s) \times G_{vcx}(s)$. Then, voltage closed-loop transfer function $G_{vivx}(s)$ of x^{th} LRC can be written as:

$$G_{vivx}(s) = \frac{G_{vdx}(s) G_{icx}(s) G_{vcx}(s)}{1 + \sum_{y=1}^n \{G_{vdy}(s) G_{icy}(s) (G_{vcy}(s) + g_y G_{iv}(s))\}} \quad (12)$$

It should be noted that $G_{vivx}(s)$ is related to x^{th} LRC's all control parameters ($G_{icx}(s)$ and $G_{vcx}(s)$) in the numerator, as well as is related to all LRCs' control parameters in the denominator. Dynamic coupling and interconnection of each $G_{vivx}(s)$ are consistent with equivalent voltage-current closed-loop transfer function $G_{viveq}(s)$ of the SLROM.

Similarly, $G_{ivdeq}(s)$ is equivalent voltage open-loop transfer function, $G_{vceq}(s)$ is the voltage controller of the SLROM, and loop gain $T_{viveq}(s)$ of voltage control can be derived as $T_{viveq}(s) = G_{ivdeq}(s) \times G_{vceq}(s)$. Then, voltage closed-loop transfer function $G_{viveq}(s)$ can be obtained.

$$G_{viveq}(s) = \frac{G_{vdeq}(s) G_{iceq}(s) G_{vceq}(s)}{1 + G_{ideq}(s) G_{iceq}(s) + G_{vdeq}(s) G_{iceq}(s) G_{vceq}(s)} \quad (13)$$

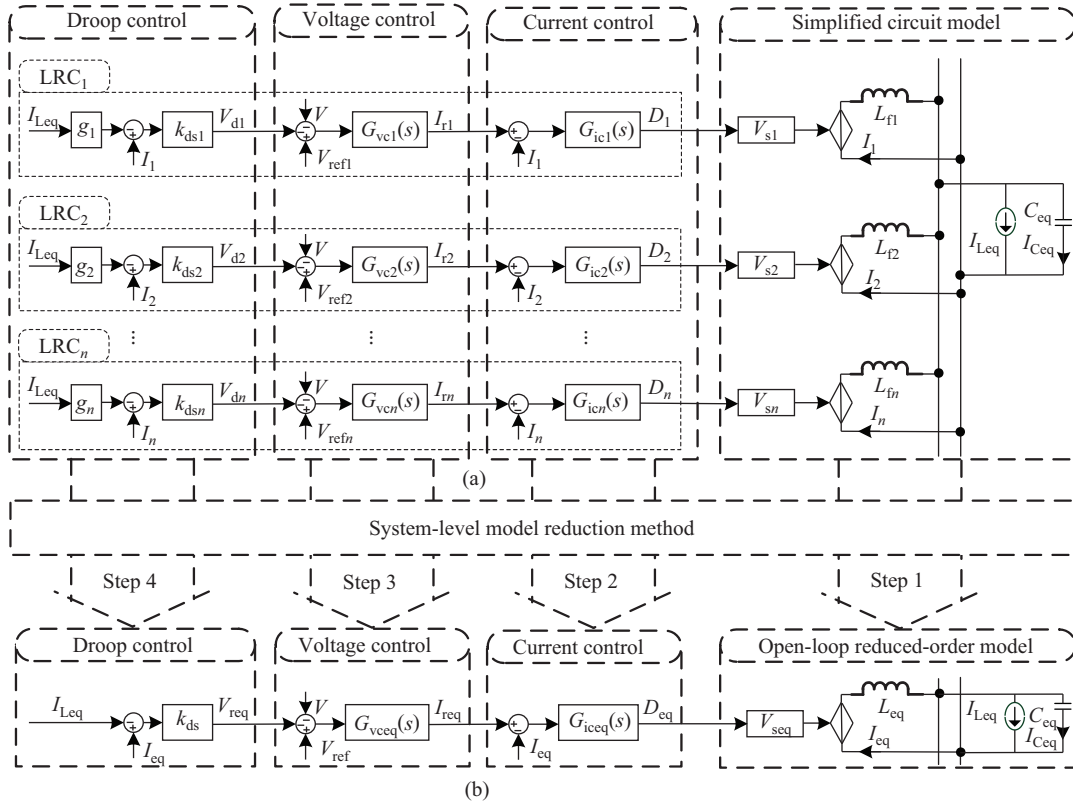


Fig. 6. Control architecture. (a) multi-converter MVDC power system. (b) Single-converter reduced-order model.

C. Step 4: System-level Reduced-order Modeling Considering Dynamic Interaction of Droop Control among Converters

In Fig. 6(a), mathematical expression of V_{rx} can be written as:

$$V_{rx} = k_{dsx}(I_x - I_{Leq}g_x) \quad (14)$$

where k_{dsx} is virtual resistance of x^{th} LRC, which is defined in (15).

$$k_{dsx} = \frac{k_{ds}}{g_x} \quad (15)$$

where k_{ds} is equivalent virtual resistance. Taking droop control into account, then voltage closed-loop transfer function $G_{sivvx}(s)$ of x^{th} LRC can be written as:

$$G_{sivvx}(s) = \frac{G_{vdx}(s)G_{icx}(s)G_{vcx}(s)}{1 + \sum_{y=1}^n \left\{ \frac{G_{vdy}(s)G_{icy}(s)\{G_{vcy}(s)\}}{(1 + k_{ds}C_{eq}s) + g_y G_{iv}(s)} \right\}} \quad (16)$$

Similarly, system level transfer function $G_{vivr\text{sys}}(s)$ is obtained by adding $G_{sivvx}(s)$ to each other, which can be written as Appendix (A-3). Where proportional and integral gains of the voltage controller $G_{vcx}(s)$ are k_{pvx} and k_{ivx} , respectively.

In Fig. 6(b), mathematical expression of V_{req} can be written as:

$$V_{req} = k_{ds}(I_L - I) = k_{ds}C_{eq}Vs \quad (17)$$

Taking droop control into account, equivalent voltage closed-loop transfer function $G_{vivr\text{eq}}(s)$ can be written as

Appendix (A-4). Where proportional and integral gains of the voltage controller $G_{vceq}(s)$ are k_{pveq} and k_{iveq} , respectively.

Because (A-3) and (A-4) are equivalent, the following mathematical formula can be obtained.

$$\begin{cases} k_{pveq} = \left(\sum_{x=1}^n \frac{k_{pix}k_{pvx}}{L_{fx}} \right) \frac{1}{\left(\sum_{x=1}^n \frac{g_x k_{pix}}{L_{fx}} \right)} \\ k_{iveq} = \left(\sum_{x=1}^n \frac{k_{iix}k_{ivx}}{L_{fx}} \right) \frac{1}{\left(\sum_{x=1}^n \frac{g_x k_{iix}}{L_{fx}} \right)} \end{cases} \quad (18)$$

where k_{pveq} is a function of k_{pix} , k_{pvx} , g_x , and L_{fx} , while k_{iveq} is a function of k_{iix} , k_{ivx} , g_x , and L_{fx} . With transfer functions shown in (18), mathematical relationships of voltage control parameters between multi-converter and equivalent single-converter systems are established.

The unstable origin can be figured out based on the bode graph of every step control loop gain and close-loop transfer functions. Moreover, theoretical guidance for which control parameters are redesigned can also be given. Furthermore, dynamic stability of the system can be analyzed by the SLMRM.

IV. THEORETICAL ANALYSIS AND EXPERIMENTAL VERIFICATION

A. Description of Test System

To verify validity of the SLMRM, three multi-converter MVDC power systems (system I, system II, and system III) are implemented in an RT-BOX hardware-in-the-loop experimental platform shown in Fig. 7. In more detail, specific

circuits and control diagrams of the three studied multi-converter MVDC power systems and their SLROMs are shown in Appendix Fig. B1.

Main circuit parameters of the three multi-converter MVDC power systems of voltage level 10 kV are shown in Tables I, II and III, respectively [19].

As can be seen in Table IV, for system I, four cases are designed: case 1, case 2, case 5 and case 6. In addition, for system II and system III, case 3 and case 4 are designed, respectively.

B. 2nd Order CLROM

To validate theoretical analysis in Part B of Section I, stability analysis of system I will be implemented by SLMRM.

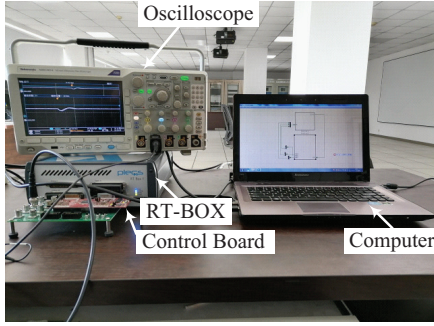


Fig. 7. RT-BOX hardware-in-the-loop experimental platform.

TABLE I
PARAMETERS OF THE SYSTEM I

Component	Parameter	Value
1 st LRC	Rated output power P_1 /MW	10
	Filter inductor L_{f1} /mH	13.3
	Filter capacitor C_{f1} /mF	0.1875
	Switching frequency f_{s1} /kHz	1
2 nd LRC	Rated output power P_2 /MW	10
	Filter inductor L_{f2} /mH	13.3
	Filter capacitor C_{f2} /mF	0.1875
	Switching frequency f_{s2} /kHz	1
CPL	Rated output power P_{eq} /MW	4
	Input filter capacitor C_{Leq} /mF	0.4
	Number	5
Cable	Cable inductor mH/km	0.47
	Cable capacitor mΩ/km	22.1
	Length /km	2
	Number	5

TABLE II
PARAMETERS OF THE SYSTEM II

Component	Parameter	Value
1 st LRC	Rated output power P_1 /MW	10
	Filter inductor L_{f1} /mH	13.3
	Filter capacitor C_{f1} /mF	0.1875
	Switching frequency f_{s1} /kHz	1
2 nd LRC	Rated output power P_2 /MW	6
	Filter inductor L_{f2} /mH	22.2
	Filter capacitor C_{f2} /mF	0.1125
	Switching frequency f_{s2} /kHz	1
CPL	Rated output power P_{eq} /MW	4
	Input filter capacitor C_{Leq} /mF	0.4
	Number	4
Cable	Cable inductor mH/km	0.47
	Cable capacitor mΩ/km	22.1
	Length /km	2
	Number	4

TABLE III
PARAMETERS OF THE SYSTEM III

Component	Parameter	Value
1 st LRC	Rated output power P_1 /MW	10
	Filter inductor L_{f1} /mH	13.3
	Filter capacitor C_{f1} /mF	0.1875
	Switching frequency f_{s1} /kHz	1
2 nd LRC	Rated output power P_2 /MW	6
	Filter inductor L_{f2} /mH	33.3
	Filter capacitor C_{f2} /mF	0.1125
	Switching frequency f_{s2} /kHz	1
3 rd LRC	Rated output power P_3 /MW	4
	Filter inductor L_{f3} /mH	22.2
	Filter capacitor C_{f3} /mF	0.075
	Switching frequency f_{s3} /kHz	1
CPL	Rated output power P_{eq} /MW	4
	Input filter capacitor C_{Leq} /mF	0.4
	Number	5
Cable	Cable inductor mH/km	0.47
	Cable capacitor mΩ/km	22.1
	Length /km	2
	Number	5

TABLE IV
CONTROL PARAMETERS OF SYSTEM I TO SYSTEM III FOR SIX CASES

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
k_{pi1}	0.0011	0.0011	0.0009	0.0011	0.0002	0.0004
k_{ii1}	0.0710	0.0710	0.0568	0.0710	0.0005	0.0131
k_{pv1}	0.1378	0.2131	0.1559	0.1830	0.2131	0.2131
k_{iv1}	8.6620	80.320	32.660	51.754	66.934	66.934
k_{ds1}	0.0800	0.0800	0.3200	0.0800	0.1200	0.1200
k_{pi2}	0.0011	0.0011	0.0025	0.0019	0.0002	0.0004
k_{ii2}	0.0710	0.0710	0.1578	0.1183	0.0005	0.0131
k_{pv2}	0.1378	0.2131	0.0936	0.1098	0.2131	0.2131
k_{iv2}	8.6620	80.320	19.596	31.052	66.934	66.934
k_{ds2}	0.0800	0.0800	0.5333	0.1333	0.1200	0.1200
k_{pi3}	—	—	—	0.0028	—	—
k_{ii3}	—	—	—	0.1775	—	—
k_{pv3}	—	—	—	0.0732	—	—
k_{iv3}	—	—	—	20.701	—	—
k_{ds3}	—	—	—	0.2000	—	—

First, substitute system I parameters in Table I into equation (3), open-loop oscillation frequency of f_{op} (ω_{op}), f_{cz} (ω_{cz}), and f_{cp} (ω_{cp}) is equal to 45 Hz, 259 Hz, and 671 Hz, respectively. Because f_{op} is not ten times smaller than f_{cz} , cable parameters cannot be ignored directly and OLROM cannot be reduced to 2nd order without control bandwidth restrictions ($f_{os} \leq 0.1 \times f_{cz} = 25.9$).

Furthermore, to avoid cable parametric oscillation from playing a critical role, dominant control bandwidth f_{os} is designed as 10 Hz in case 1. Voltage-current double-loop transfer function $G_{vivreq_cable}(s)$, considering cable parameters, is obtained, and depicted by the blue line in Fig. 8 and Fig. 9(a). As well as, substituting case 1 control parameters into equation (A-4), 4th order CLROM $G_{vivreq}(s)$ is also achieved and represented successfully by the black line in Fig. 8 and Fig. 9(b), because cable parameters can be neglected (f_{os} (10 Hz) $\leq 0.1 \times f_{cz}$ (25.9 Hz)). Undoubtedly, as shown in Fig. 8, full-order system-level model $G_{vivreq_cable}(s)$ can be perfectly simplified to 4th order SLROM.

In addition, the bode plot of CLROM $G_{vivreq}(s)$ has clear characteristics of a 2nd order system in Fig. 8. This feature is much more apparent in Fig. 9(b). A pair of conjugate poles ($f_s = 10.5$ Hz, $\zeta_s = 0.396$), which is closest to the imaginary

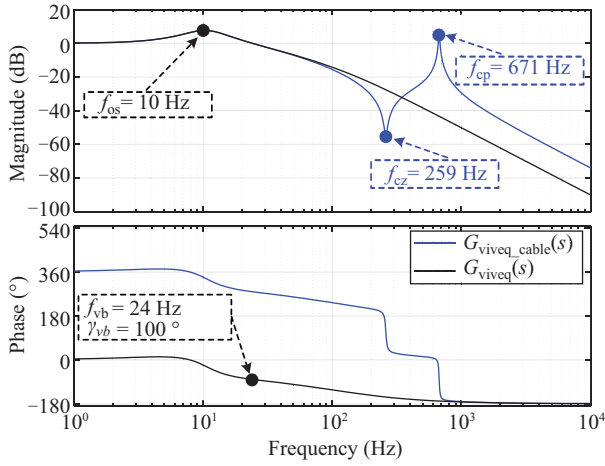
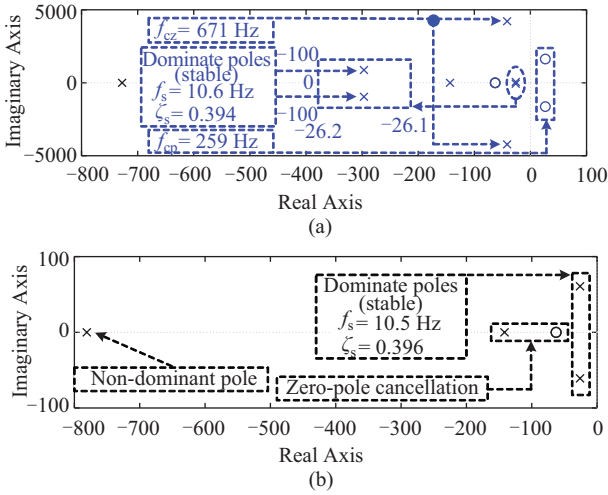


Fig. 8. Bode diagram of the SLROM under case 1.

Fig. 9. Zero-pole diagram of case 1. (a) $G_{vivreq_cable}(s)$. (b) $G_{vivreq}(s)$.

axis, can be regarded as dominant pole. Since another pole farthest from the imaginary axis cannot play a leading role, the other pole and zero cancel each other out. Therefore, 4th order CLROM $G_{vivreq}(s)$ can be accurately evaluated by the second-order model, as shown in (19), which is constructed with the oscillation frequency and damping factor of dominant poles.

$$G_{two}(s) = s^2 + 52.41s + 4384 \quad (19)$$

Finally, experimental verifications for multi-converter MVDC power system and its SLROM have been provided individually. At 0.4 seconds, constant power loads (CPLs) in system I change from 15 MW to 20 MW. Corresponding results plotted in Fig. 10(a) and (b) represent significantly uniform steady-state and dynamic performance of DC bus voltage between multi-converter MVDC power system and its SLROM. Then, accuracy of 2nd order mathematical transfer functions is verified, revealing dynamic interaction mechanism among converters. As can be seen, oscillation frequency of experimental results in Fig. 10 is about 10.32 Hz, which is consistent with theoretical analysis value of 10.5 Hz in Fig. 9. Consequently, effectiveness and convenience of the proposed

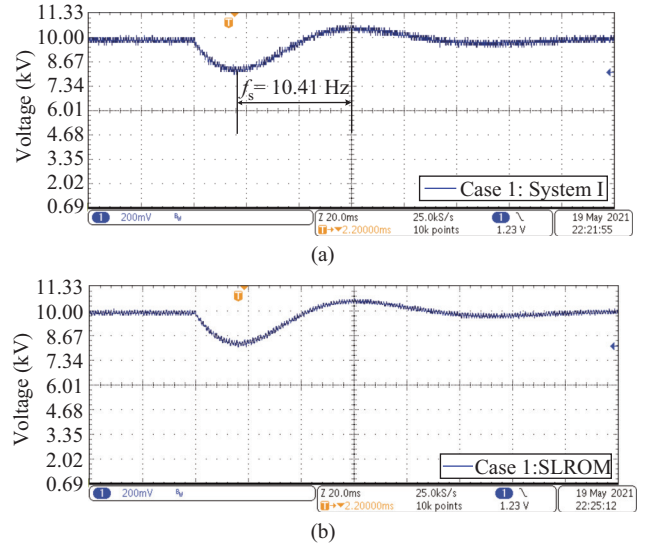


Fig. 10. Experimental waveforms of case 1. (a) system I. (b) SLROM.

SLMRM have been verified, which means that SLROM can be easily reduced to 2nd order, and dynamic stability analysis can be done successfully by the SLMRM.

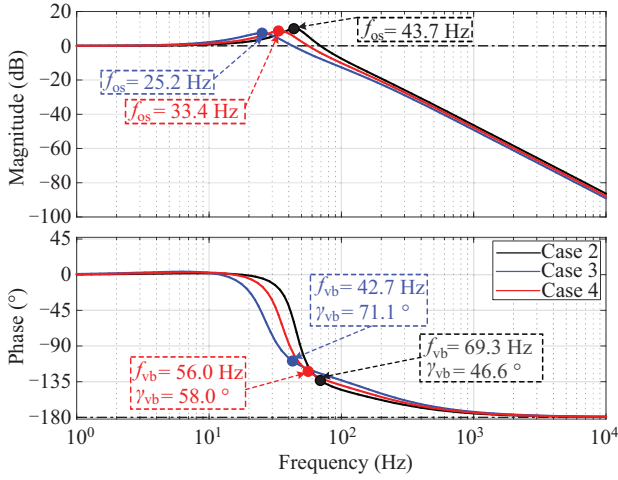
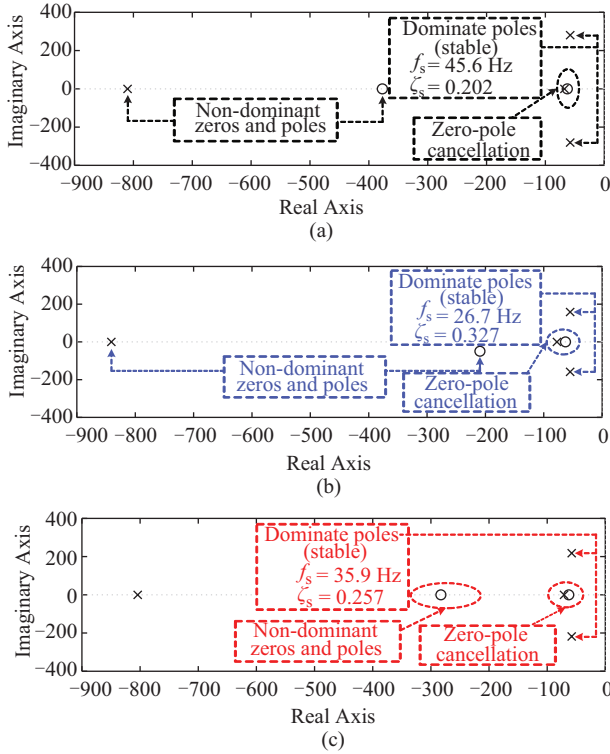
C. Dynamic Stability Analysis

Effectiveness of the SLMRM will be verified by experimental results of case 2 to 4. In case 2, parameters (including filter and control parameters) of the two converters in system I are identical. In contrast to system I, parameters of the two converters in system II (as detailed in case 3) are different from each other. For system III with three converters, as listed in case 4, parameters are different among each converter.

Substituting relevant system and control parameters into equation (A-4), frequency-response curves of CLROM $G_{vivreq}(s)$ are shown in Fig. 11. From frequency-response curves of the transfer function $G_{vivreq}(s)$, it can be derived that CLROM can evaluate different second-order model characteristics for case 2, 3 and 4, respectively. The above conclusions can also be verified by the zero-pole diagram shown in Fig. 12 intuitively. Furthermore, analytical solutions of oscillation frequencies and damping factors for case 2, 3 and 4 can be calculated based on the above three second-order models (three pairs of conjugate poles, case 2: $f_s = 45.6$ Hz, $\zeta_s = 0.202$; case 3: $f_s = 26.7$ Hz, $\zeta_s = 0.327$; case 4: $f_s = 35.9$ Hz, $\zeta_s = 0.257$), respectively.

Experimental verifications have been provided in Fig. 13. At 0.4 seconds, constant power loads in system I (under case 2) and system III (under case 4) change from 15 MW to 20 MW, while constant power loads in system II (under case 3) change from 12 MW to 16 MW.

Corresponding results show previously uniform steady-state and dynamic performance of DC bus voltage between multi-converter MVDC power system and its SLROM. In addition, control hardware in loop results of case 2, case 3 and case 4 in Fig. 13 represent significantly uniform oscillation frequency and damping factor following theoretical result in Fig. 12. By comprehensively analyzing corresponding results in Figs. 8 and 13, it is demonstrated the theoretical analysis results based

Fig. 11. Bode diagram of $G_{vivreq}(s)$ under case 2, case 3 and case 4.Fig. 12. Zero-pole diagram of $G_{vivreq}(s)$. (a) case 2. (b) case 3. (c) case 4.

on the SLMRM have very high accuracy in a wide oscillation frequency range from 10 to 50 Hz. Moreover, accuracy of the CLROM is not affected by difference of control parameters and number of the converters in the system.

D. Instability Mechanism Understanding

Effectiveness of the SLMRM, such as understanding of instability mechanism and theoretical guidance of control parameters adjustment (the flow chart is shown in Fig. 14), is verified in this section by comparing case 5 and case 6. The zero-pole diagram is shown in Fig. 15. The bode diagrams of $T_{iieq}(s)$, $T_{viveq}(s)$, $G_{iieq}(s)$ (A-2), and $G_{vivreq}(s)$ (A-4) are shown in Figs. 16 and 17, respectively.

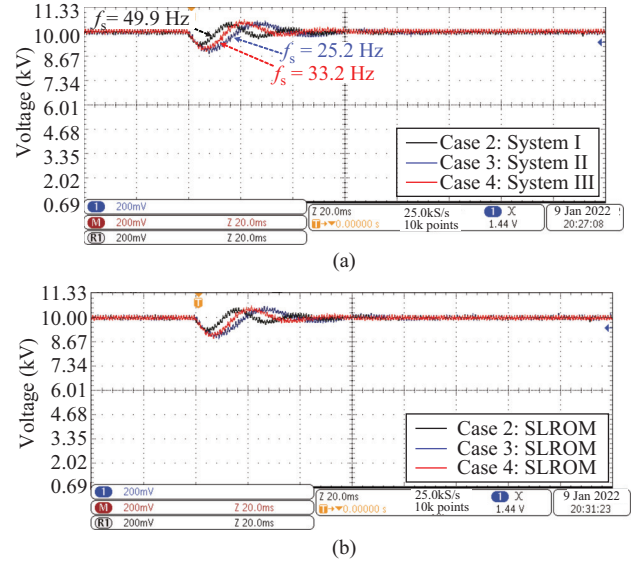


Fig. 13. Experimental results of case 2 and case 3. (a) system I, II and III. (b) SLROM.

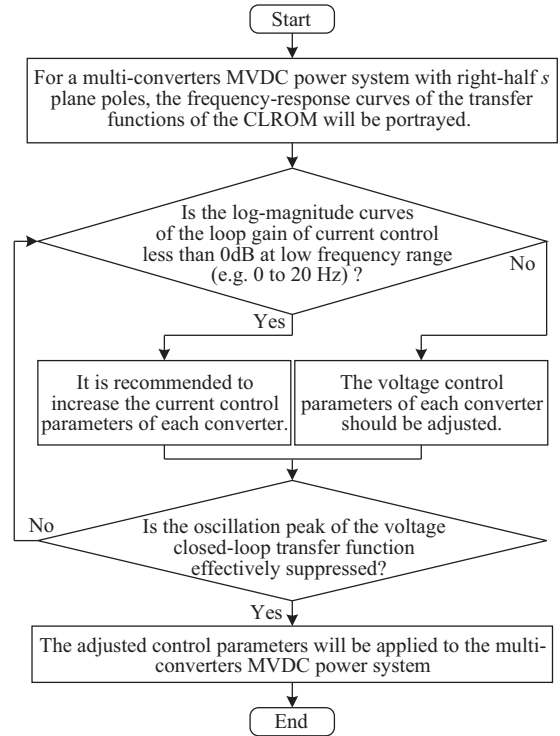


Fig. 14. Flow chart for understanding instability mechanism and theoretical guidance of control parameters adjustment.

First, dynamic stability of case 5 should be judged via (A-4). As shown in Fig. 15, a pair of conjugate poles lie in right-half s plane, which means that system I is unstable under case 5. Therefore, it is urgent to investigate the instability mechanism.

Additionally, the origin of instability should be figured out. As shown in Fig. 16, log-magnitude curves of $T_{iieq}(s)$ and $G_{iieq}(s)$ are less than 0 dB at frequencies below 20 Hz, which is not rational. In addition, as shown in Fig. 17, a larger oscillation peak appears in the log-magnitude curve of $G_{vivreq}(s)$ around 46.5 Hz, and it is found the phase margin

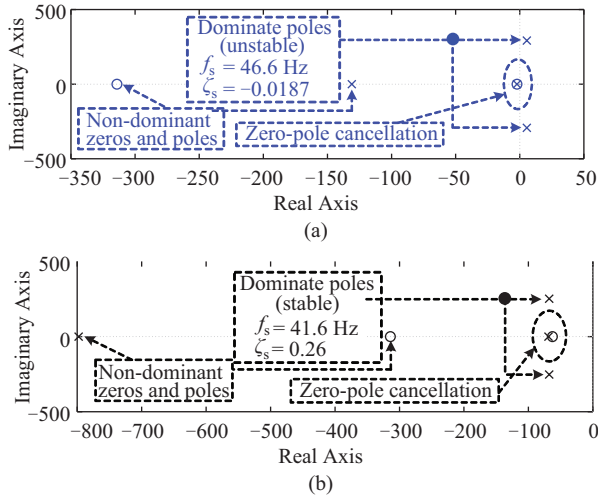


Fig. 15. Zero-pole diagram of $G_{vivreq}(s)$: (a) case 5. (b) case 6.

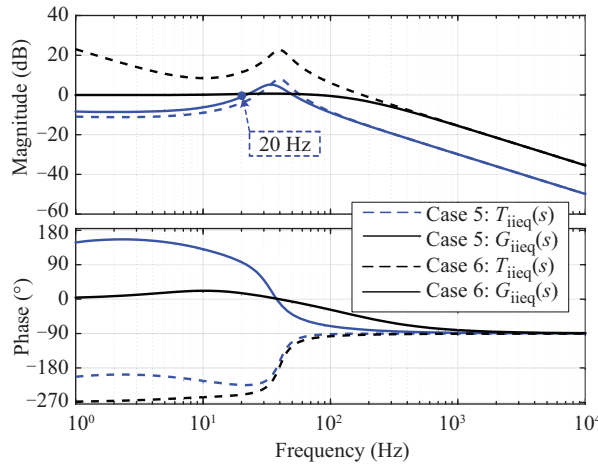


Fig. 16. Bode diagram of $T_{iiq}(s)$ and $G_{iiq}(s)$ under case 5 and case 6.

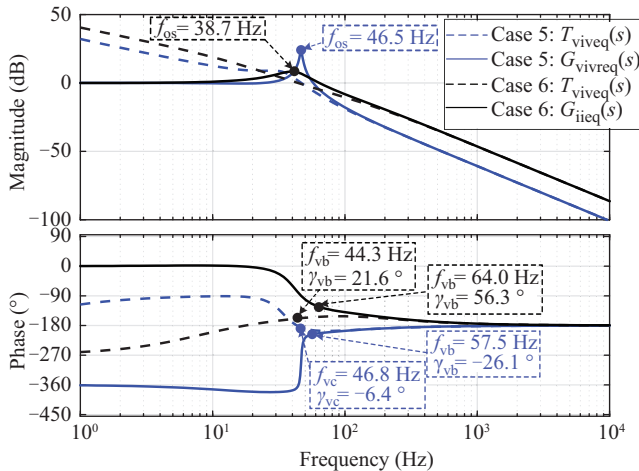


Fig. 17. Bode diagram of $T_{viveq}(s)$ and $G_{viveq}(s)$ under case 5 and case 6.

of $G_{vivreq}(s)$ is -26.1° . Consequently, it can be inferred the proportional and integral gains of the current controller are too small, which is the instability mechanism of system I under case 5.

Finally, unreasonable control parameters should be adjusted

and dynamic stability of the system should be re-evaluated by the CLROM. As shown in Fig. 16, after changing current control parameters of the 1st converter, the log-magnitude curve of $T_{iiq}(s)$ under case 6 is greater than 0 dB at frequencies below 20 Hz. In addition, as shown in Fig. 17, a small oscillation peak appears in log-magnitude curve of $G_{vivreq}(s)$ around nearly 38.7 Hz, and it is found the phase margin is 56.3° . Consequently, stability of system I can be improved by adjusting current control parameters.

Under the same disturbance condition of system I, experimental results of case 5 and case 6 are demonstrated in Fig. 18. System I is unstable after wide variation of loads by experiment result of case 5. Steady-state and dynamic performance of DC bus voltage of system I and its SLROM are significantly consistent. Then, validity of these mathematical transfer functions $G_{vivreq}(s)$ is verified, even if system I is unstable after loads disturbance.

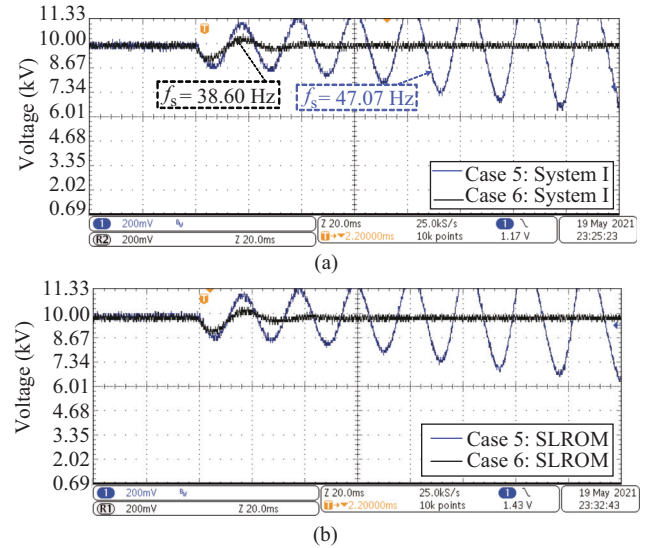


Fig. 18. Experimental waveforms. (a) System I. (b) SLROM.

Unstable oscillation frequency of case 5 in Fig. 18 is about 47.07 Hz, which is consistent with theoretical value of 46.6 Hz in Fig. 15. By adjusting current control parameters, the excited oscillations are damped in a short period. In addition, oscillation frequency (38.6 Hz) of case 6 is significantly consistent with theoretical value (41.6 Hz) shown in Fig. 15.

Corresponding results, which are plotted in Figs. 15 to 18, demonstrate the instability mechanism of the system based on those open-loop and closed-loop ROM can be revealed intuitively. More importantly, stability of the system can be improved by adjusting control parameters according to the adjustment scheme provided by the SLMRM.

V. CONCLUSION

The SLMRM introduced in this paper has been proved to be an effective tool for simplifying dynamic stability analysis of multi-converter MVDC power system. Equivalent OLROM and CLROM are established in four steps according to this method. In the reduced-order modeling procedure, all kinds of control dynamics of each converter, such as

voltage, current, and droop control have never be ignored. On the contrary, mathematical relationships of all parameters (e.g., filter parameters, current control, voltage control, and droop control parameters) between the multi-converter MVDC power system and equivalent single-converter system have been established step-by-step considering dynamic interaction among converters.

With the proposed equivalent ROM, computational complexity of dynamic stability analysis for the multi-converter MVDC power system can be reduced significantly. There are only four poles and two zeros in the CLROM transfer function $G_{\text{vivreq}}(s)$. The two zeros are generated by equivalent voltage controller and current controller, respectively. Their analytical expressions can be given directly. Oscillation frequency and damping factor of DC bus voltage in a wide oscillation frequency range (e.g., 10–50 Hz) can be evaluated accurately. Moreover, accuracy of the CLROM is not affected by difference of control parameters and number of the converters.

With the proposed SLMRM, the instability mechanism can be revealed intuitively. Because every step (current, voltage, and droop control) transfer function of the CLROM is established, reflecting the comprehensive dynamics of each converter in the system intuitively step by step. For instance, when current control parameters of each converter are too small, log-magnitude curve of $G_{\text{iieq}}(s)$ will be less than 0 dB at frequencies below its control bandwidth. At the same time, log-magnitude curve of $G_{\text{vivreq}}(s)$ will have a large oscillation peak, and its phase margin will be less than 0°. More importantly, stability of the system can be improved by adjusting control parameters according to the adjustment scheme provided by individual CLROM. From experimental results, CLROM can reflect DC bus voltage dynamic and steady-state characteristics accurately.

Suppose there are some converters connected/disconnected from the system, and system topology and parameters will change accordingly. In view of this situation, how to further analyze large signal stability of multi-converter MVDC power system is our future work.

APPENDIX A

$$G_{\text{iisys}}(s) = \frac{\sum_{x=1}^n \left\{ \frac{V_{sx}g_x}{C_{eq}L_{fx}} \left(k_{pix}C_{eq}s^2 + \left(k_{iix}C_{eq} - \frac{k_{pix}}{R_{eq}} \right) s - \frac{k_{iix}}{R_{eq}} \right) \right\}}{s^3 + \left\{ \sum_{x=1}^n \left(\frac{V_{sx}g_x}{C_{eq}L_{fx}} (k_{pix}C_{eq}) \right) - \frac{1}{C_{eq}R_{eq}} \right\} s^2 + \left\{ \sum_{x=1}^n \left(\frac{V_{sx}g_x}{C_{eq}L_{fx}} \left(k_{iix}C_{eq} - \frac{k_{pix}}{R_{eq}} \right) \right) + \frac{1}{C_{eq}L_{eq}} \right\} s - \sum_{x=1}^n \left(\frac{V_{sx}k_{iix}g_x}{C_{eq}L_{fx}R_{eq}} \right)} \quad (\text{A-1})$$

$$G_{\text{iieq}}(s) = \frac{\frac{V_s}{C_{eq}L_{eq}} \left(k_{pieq}C_{eq}s^2 + \left(k_{iieq}C_{eq} - \frac{k_{pieq}}{R_{eq}} \right) s - \frac{k_{iieq}}{R_{eq}} \right)}{s^3 + \left(\frac{V_s}{C_{eq}L_{eq}} (k_{pieq}C_{eq}) - \frac{1}{C_{eq}R_{eq}} \right) s^2 + \left(\frac{V_s}{C_{eq}L_{eq}} \left(k_{iieq}C_{eq} - \frac{k_{pieq}}{R_{eq}} \right) + \frac{1}{C_{eq}L_{eq}} \right) s - \left(\frac{V_s k_{iieq}}{C_{eq}L_{eq}R_{eq}} \right)} \quad (\text{A-2})$$

$$G_{\text{vivrsys}}(s) = \frac{\sum_{x=1}^n \left\{ \frac{V_{sx}}{C_{eq}L_{fx}} (k_{pix}s + k_{iix})(k_{pvx}s + k_{ivx}) \right\}}{\left\{ s^4 + \left\{ \sum_{x=1}^n \left(\frac{V_{sx}}{C_{eq}L_{fx}} (k_{pix}C_{eq}g_x + k_{pix}k_{pvx}k_{ds}C_{eq}) \right) - \frac{1}{C_{eq}R_{eq}} \right\} s^3 + \left\{ \sum_{x=1}^n \left\{ \frac{V_{sx}}{C_{eq}L_{fx}} \left(k_{pix}k_{pvx} + g_x \left(k_{iix}C_{eq} - \frac{k_{pix}}{R_{eq}} \right) + (k_{pix}k_{ivx} + k_{iix}k_{pvx})k_{ds}C_{eq} \right) \right\} + \frac{1}{C_{eq}L_{eq}} \right\} s^2 + \left\{ \sum_{x=1}^n \left\{ \frac{V_{sx}}{C_{eq}L_{fx}} \left(k_{pix}k_{ivx} + k_{iix}k_{pvx} + k_{iix}k_{ivx}k_{ds}C_{eq} - \frac{k_{iix}g_x}{R_{eq}} \right) \right\} \right\} s + \sum_{x=1}^n \left(\frac{V_{sx}}{C_{eq}L_{fx}} k_{iix}k_{ivx} \right) \right\}} \quad (\text{A-3})$$

$$G_{\text{vivreq}}(s) = \frac{\frac{V_s}{C_{eq}L_{eq}} (k_{pieq}s + k_{iieq})(k_{pveq}s + k_{iveq})}{\left\{ s^4 + \left\{ \frac{V_s}{C_{eq}L_{eq}} (k_{pieq}C_{eq} + k_{pieq}k_{pveq}k_{ds}C_{eq}) - \frac{1}{C_{eq}R_{eq}} \right\} s^3 + \left\{ \frac{V_s}{C_{eq}L_{eq}} \left(k_{pieq}k_{pveq} - \frac{k_{pieq}}{R_{eq}} + k_{iieq}C_{eq} + (k_{pieq}k_{iveq} + k_{iieq}k_{pveq})k_{ds}C_{eq} \right) + \frac{1}{C_{eq}L_{eq}} \right\} s^2 + \left\{ \frac{V_s}{C_{eq}L_{eq}} \left(k_{pieq}k_{iveq} + k_{iieq}k_{pveq} + k_{iieq}k_{iveq}k_{ds}C_{eq} - \frac{k_{iieq}}{R_{eq}} \right) \right\} s + \frac{V_s}{C_{eq}L_{eq}} (k_{iieq}k_{iveq}) \right\}} \quad (\text{A-4})$$

APPENDIX B

As shown in Fig. B1, for system I, $m = 5$; and for system II, $m = 4$.

The circuit parameters of the SLROMs of the three studied multi-converter MVDC power systems are shown in Tables BI to BIII, respectively.

The control parameters of the SLROM under case 1 to 6 are shown in Table BIV.

The reason, why case 1 to 6 denote different dynamic stability characteristics, will be explained from the perspective of the SLROM. For case 1, case 2, case 3, case 4 and case 6,

the Bode diagrams of the transfer functions $T_{\text{iieq}}(s)$, $G_{\text{iieq}}(s)$, $G_{\text{ivdeq}}(s)$, $T_{\text{viveq}}(s)$ and $G_{\text{vivreq}}(s)$ of the SLROM are shown in Figs. B2 to B6, respectively.

The circuit parameters and current control parameters of the SLROM are identical for case 1, case 2, case 4 case 6. The corresponding parameters of case 3 (including circuit parameters and current control parameters) are slightly different with the four cases mentioned above. However, the frequency response curves of the current control transfer functions $T_{\text{iieq}}(s)$ and $G_{\text{iieq}}(s)$ for these four cases are consistent, as shown in Figs. B2 and B3. Therefore, the main reason for the different

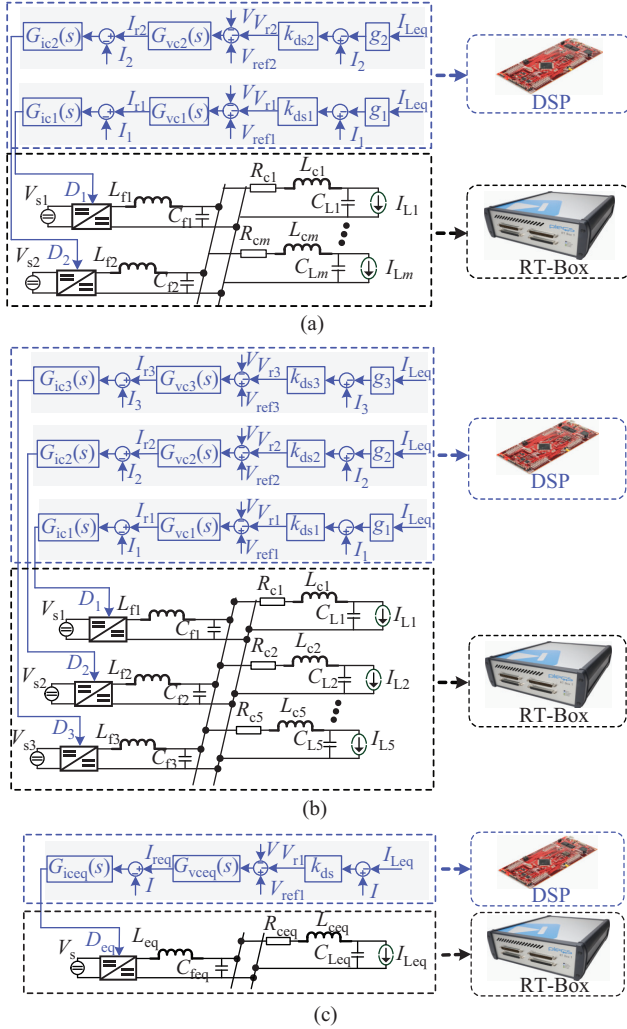


Fig. B1. The specific circuit and control diagram: (a) system I and II. (b) system III. (c) SLROM.

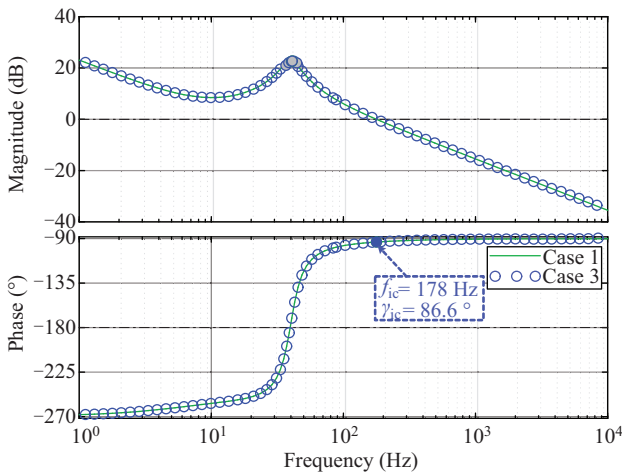


Fig. B2. Bode diagram of $T_{ii}(s)$ under case 1 and case 3.

dynamic stability of case 1, case 2, case 3, case 4 and case 6 is the voltage control parameters. Increasing the voltage control parameters, the crossover frequency of the loop gain $T_{viveq}(s)$ will increase with the reduced phase margin, as detailed in

TABLE BI
PARAMETERS OF THE SLROM OF SYSTEM I

Component	Parameter	Value
SLROM	Rated output power P_{eq}/MW	20
	Filter inductor L_{eq}/mH	6.7
	Filter capacitor C_{feq}/mF	0.375
	Switching frequency f_s/kHz	1
CPL	Rated output power P_{eq}/MW	20
	Input filter capacitor C_{Leq}/mF	2
Cable	Cable inductor mH	0.094
	Cable capacitor $\text{m}\Omega$	4.42

TABLE BII
PARAMETERS OF THE SLROM OF SYSTEM II

Component	Parameter	Value
SLROM	Rated output power P_{eq}/MW	16
	Filter inductor L_{eq}/mH	8.3
	Filter capacitor C_{feq}/mF	0.3
	Switching frequency f_s/kHz	1
CPL	Rated output power P_{eq}/MW	16
	Input filter capacitor C_{Leq}/mF	1.6
Cable	Cable inductor mH	0.1175
	Cable capacitor $\text{m}\Omega$	5.525

TABLE BIII
PARAMETERS OF THE SLROM OF SYSTEM III

Component	Parameter	Value
SLROM	Rated output power P_{eq}/MW	20
	Filter inductor L_{eq}/mH	6.7
	Filter capacitor C_{feq}/mF	0.375
	Switching frequency f_s/kHz	1
CPL	Rated output power P_{eq}/MW	20
	Input filter capacitor C_{Leq}/mF	2
Cable	Cable inductor mH	0.094
	Cable capacitor $\text{m}\Omega$	4.42

TABLE BIV
CONTROL PARAMETERS OF THE SLROM FOR SIX CASES

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
k_{pieq}	0.0006	0.0006	0.0007	0.0006	0.0001	0.0006
k_{iieq}	0.0355	0.0355	0.0444	0.0355	0.0002	0.0355
k_{pveq}	0.2757	0.4261	0.2495	0.3661	0.4261	0.4261
k_{iveq}	17.324	160.64	52.256	103.51	133.87	133.87
k_{ds}	0.0400	0.0400	0.2000	0.0400	0.0600	0.0600

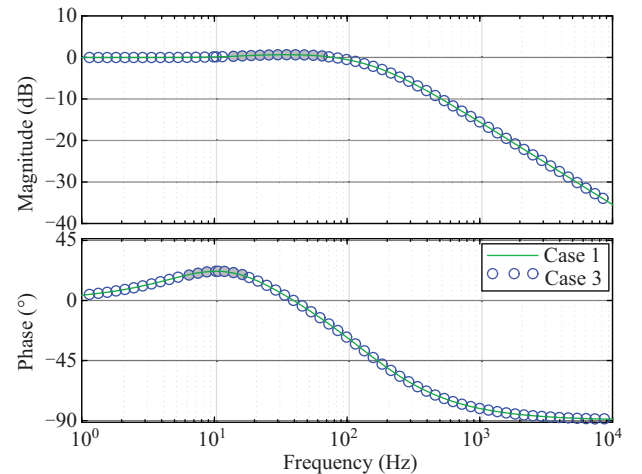


Fig. B3. Bode diagram of $G_{ii}(s)$ under case 1 and case 3.

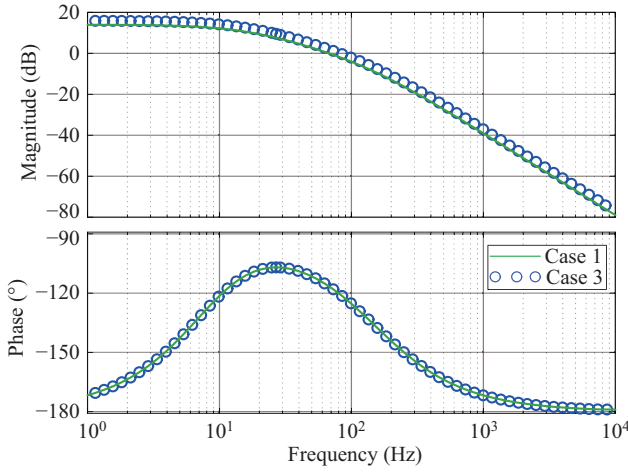
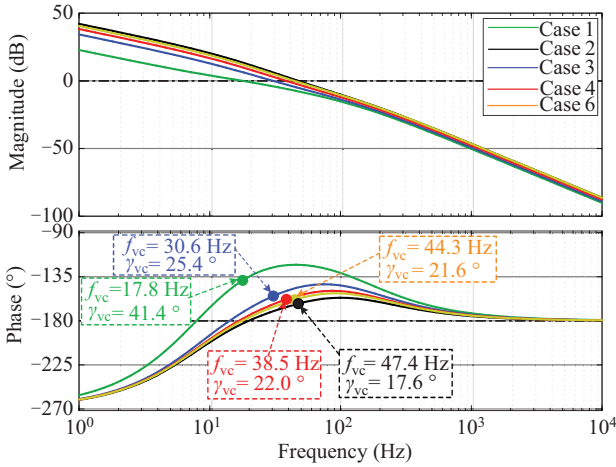
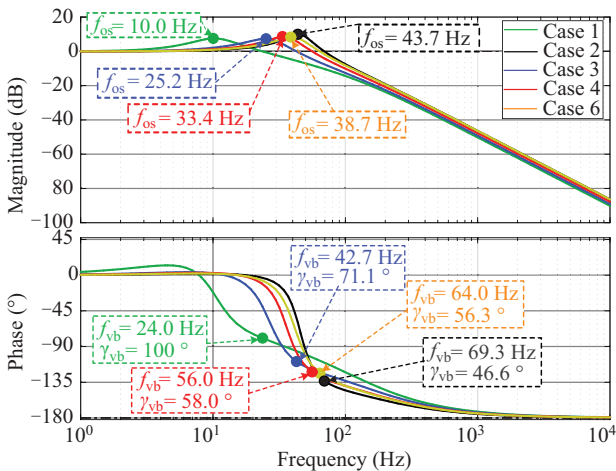
Fig. B4. Bode diagram of $G_{ivdeq}(s)$ under case 1 and case 3.Fig. B5. Bode diagram of $T_{viveq}(s)$ under case 1, case 2, case 3, case 4 and case 6.Fig. B6. Bode diagram of $G_{vivreq}(s)$ under case 1, case 2, case 3, case 4 and case 6.

Fig. B5. It means that the oscillation frequency of the SLROM will increase with the reduced damping factor, as shown in Figs. 9, 12 and 15.

Comparing case 5 and case 6, it can be seen that the phase

margin of the loop gain $T_{viveq}(s)$ will be reduced by decreasing the current control parameters. When the phase margin of the loop gain $T_{viveq}(s)$ is negative, the multi-converter MVDC power system and its SLROM will be unstable.

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Li Guo received B.S. and Ph.D. degrees in Electrical Engineering from South China University of Technology in 2002 and 2007, respectively. Dr. Guo is currently a full Professor at Tianjin University. His research interests include the optimal planning and design of microgrid, and the advanced energy management system.



Bo Zhao received the Ph.D. degree from Zhejiang University, Hangzhou, China, in 2005. He is currently an Engineer with the State Grid Zhejiang Electric Power Research Institute, Hangzhou, China. His research interests include distributed generation microgrids.



Lin Zhu received the B.S. and M.S. degrees from China Agriculture University, Beijing, China, in 2008 and 2010, respectively, and the Ph.D. degree from RWTH Aachen University, Aachen, Germany, in 2018, all in Electrical Engineering. Since 2010, she has been a Research Associate with the Institute of Automation of Complex Power Systems, E.ON Energy Research Center, Aachen, Germany. Since 2019, she has been a Lecturer with the School of Electrical Engineering and Automation, Tianjin University, Tianjin, China. Her research interests

include stability analysis, control and hardware in the loop simulation in DC, and hybrid AC/DC power systems.



Zhanfeng Deng is director of the Institute of power electronics in State Grid Smart Grid Research Institute Co. Ltd., Beijing, China. His main research interests include energy storage materials, energy storage system and power electronics technology theory.



Xueshen Zhao received the B.S. and M.S. degrees in Electrical Engineering from Shandong University of Technology, Shandong, China, in 2016 and 2019, respectively. His research interests include stability analysis and optimal control of DC distribution system.



Hao Lu received the B.S. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 2020. He is currently working toward the M.E. degree at Tianjin University. His research interests include stability analysis, control in DC power system.



Xialin Li received the B.S. and Ph.D. degrees from Tianjin University, Tianjin, China, in 2009 and 2014, respectively. Since 2014, he has been a Lecturer with the School of Electrical Engineering and Automation, Tianjin University, China. His current research interests include the modeling and control of power converters.



Chengshan Wang received the Ph.D. degree in Electrical Engineering from Tianjin University, Tianjin, China, in 1991. From 1994 to 1996, he was a Senior Academic Visitor with Cornell University, Ithaca, NY, USA. From 2001 to 2002, he was a Visiting Professor with Carnegie Mellon University, Pittsburgh, PA, USA. He is currently a Professor with the School of Electrical Engineering and Automation, Tianjin University, where he is also the Director of the Key Laboratory of Smart Grid of Ministry of Education. His current research interests

include distribution system analysis and planning, distributed generation system and micro-grid, and power system security analysis.